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Solar sorption refrigeration in Africa

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ABSTRACT

Solar sorption refrigeration technologies are regarded as a promising way to meet the growing refrigeration needs in Africa, for thermal comfort, foods and crops, vaccines and medicines conservation. Sorption technologies projects and studies have been reported in Africa since the late 1970s. This paper describes the most representative reported research activities and projects in various African climatic conditions. An emphasis is put on demonstrative plants involving absorption, adsorption or desiccant cooling applications. From this overview, it appears that a lot of achievements have been made, though applications are mainly focused on small-size cold boxes for foods and vaccines preservation; no direct building air conditioning based on adsorption or absorption has been reported. Mediterranean countries seems to offer the best weather conditions for solar sorption refrigeration applications and plenty of related activities could be identified in these countries. A more adequate design for each of other climatic zones in Africa may then be relevant. As anywhere, the high cost of these technologies remains the main the biggest brake to their diffusion in Africa.

Contents

Abbreviations: AdSR, adsorption refrigerator; ANN, artificial neural network; COP, coefficient of performance; ID, inner diameter; NGO, non-governmental organisation; PVPR, photovoltaic powered refrigerator; OD, outer diameter; SAbIM, solar absorption ice maker; SAdIM, solar adsorption ice maker; SR, sorption refrigerator

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1. Introduction

On the road to development, the African continent, especially Sub-Saharan Africa, is delayed by a major problem of extremely low energy services accessibility and a poor level of energy consumption. While in Northern Africa, access to electricity is higher than 90%, the electrical plants of the whole fifty sub-Saharan countries, except South Africa, are equivalent to that of Argentina (generation capacity: 28 GW) [1,2] and hardly the fifth of the population in this area has access to electricity. Moreover, in the areas of this region, where an electrical grid exists, there is frequently power outage in the year, mostly in dry or hot seasons. At the same time, thermal comfort needs are growing in the sub-Saharan African countries, including the use of air conditioning due to the economic development that creates a higher living and working standards. As stated above, in most of the sub-Saharan countries, power outage is severe in hot seasons, exactly when thermal comfort is needed since the cooling load and the solar insolation availability are concomitant. Furthermore, the fraction of the produced electricity devoted to air conditioning may be very high (60% in Ouagadougou, Burkina Faso; 32% of the electrical energy consumed by the domestic sector in Egypt [3,4]). The need of refrigeration – cold production either for chilling, cooling or air conditioning – in sub-Saharan region is not only for air conditioning but also for food preservation, including in the countryside, where more than 70% of the population actually lives. Food preservation is not only a health issue but also an economic one because a big part of the harvest including dairy products is lost in African rural areas due to lack of refrigeration systems. The same applies for drugs and vaccines conservation.

However, the abundance of energy resources (solar, coal, oil, gas, uranium (nuclear), hydroelectric power potential, wind, biomass), which are only lightly exploited for the moment, can make scandal. Africa has exceptional insolation conditions (between 16 and 30 MJ m^{-2} day^{-1} of solar insolation) and its refrigeration needs can be largely satisfied by solar-assisted refrigeration applications, if the latter become economically viable.

Two main solar refrigeration technologies are available: the photovoltaic powered refrigeration technologies and the solar thermal powered refrigeration technologies (Fig. 1).

In Africa, the encountered photovoltaic powered refrigeration technology uses photovoltaic panels (PV) to supply electricity to a conventional vapour compression refrigeration cycle. Assuming an efficiency of 10–15% for PV panels and a coefficient of performance (COP) of 3 for the vapour compression refrigeration cycle, the overall or solar COP of a PV powered refrigerator (PVPR) is about 0.30–0.45. Compared to refrigerators that utilise fuels (kerosene), they have the advantages of having their energy source on site and of being environmental friendly. PVPRs have been mainly promoted in Africa by international health promotion organisations, such as the World Health Organisation (WHO), which use PVPRs to keep vaccines and drugs cold [5]. The high specific value of the latter products explains the commercial success of PVPRs in spite of various limits, the first of which is the high price of the complete system. In fact, some limits of this application have been pointed by Iloje and Enibe [5], who have prospected solar cooling for Africa – both PV and sorption machines – in a report published in 1995. PVPRs are relatively expensive and currently, a PV manufacture could hardly be identified in Africa (only few PV manufactories could be identified in South Africa).

In the usual applications of solar thermal powered refrigeration, solar thermal collectors (flat-type collectors, evacuated tubes, parabolic troughs) supply heat to a sorption machine (adsorption or absorption). Sorption refrigerators (SRs) are easier to be produced in Africa because they require widely held skills in many Africans countries [5]. SR has no or very few moving parts, thus no or very little maintenance is required; therefore, sorption refrigeration is a reliable technology in Africa where a lot of projects failed because of lack of maintenance. Since there is no moving part, no additional electricity supply is required and there is no operating cost. SRs are environmentally friendly and no harmful refrigerant is used. They are cheaper than PVPRs (Fig. 2) [6,7] although a quick look on the prices suggested for various commercial small power SRs suggests that this actually remains a challenge. The SR technology exhibits however some disadvantages. They are very bulky for a small refrigeration power, which makes transportation difficult [5]. In addition, their performance are depends not only on the solar insolation, they are also highly sensitive to the ambient conditions (temperature and eventually wind). Furthermore, solar SRs show low solar COPs (typically about 0.1).

In this paper, an overview of solar sorption refrigeration applications and research activities in Africa is addressed in order to highlight the potential of this technology in Africa and barriers that have to be overcome.

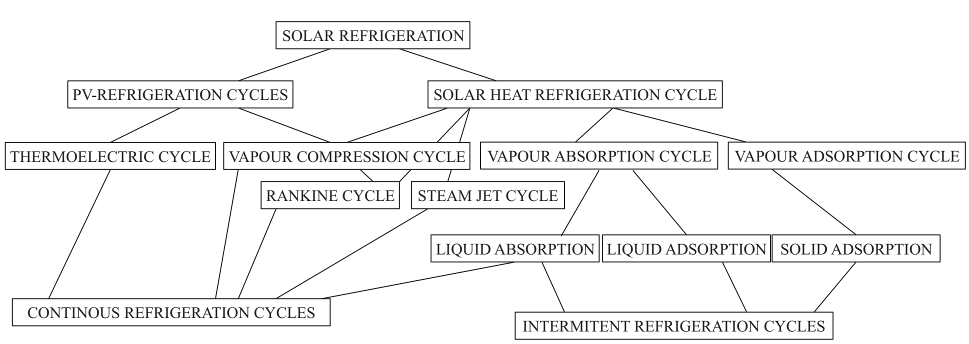


Fig. 1. Classification of solar refrigeration cycles [27].

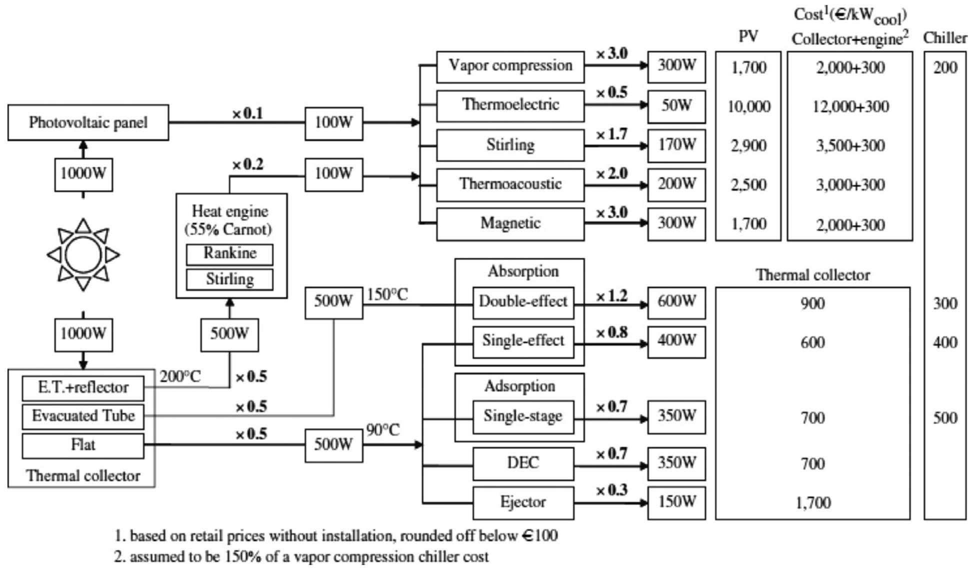


Fig. 2. Performance and cost of various solar refrigeration systems [7]. Costs are given in an European context (period: around 2007).

2. Operating principle and comparison of the main sorption refrigeration technologies

2.1. Operating principle of the main sorption refrigeration technologies

Sorption refrigeration processes have been extensively studied [8] and are only briefly introduced here. There are currently three main cold production processes based on sorption, each of these technologies may be continuous or intermittent, closed or open process with many variations.

2.1.1. Absorption refrigeration technology

Absorption machines use a liquid–gas working pair, i.e. a working fluid that is a mixture of a refrigerant and an absorbent. The absorbent has a high affinity towards the refrigerant i.e. it exhibits a strong potential to absorb the vapour phase of the refrigerant. An absorption machine consists of four main components: a desorber, an absorber, a condenser and an evaporator. A schematic of a basic close absorption refrigeration cycle is depicted in Fig. 3. In the desorber, solar heat is supplied to the working fluid. The working fluid increases in temperature and releases the refrigerant (vapour), which flows into the condenser where it is condensed. The absorbent obtained at the end of desorption is circulated from the desorber to the absorber while the liquid refrigerant resulting from the condensation drops in the evaporator, where it is evaporated by heat from the load. The vapour produced is then absorbed in the absorber by the absorbent and the resulting mixture is circulated to the desorber.

Depending on the design of the process, various additional components would be required, mostly a solution heat exchanger in order to increase the COP of the process. The most used absorption working pairs are LiBr/H_2O and H_2O/NH_3 where NH_3 is the refrigerant and allows achieving negative temperatures.

2.1.2. Adsorption refrigeration technology

An adsorption cycle is similar to that of absorption. Here, the sorbent is a solid (adsorbent), which adsorbs and releases a refrigerant according to the cycle phase. Due to the fact that there is no circulation of the solid adsorbent, various adsorption cycles are intermittent and operate with two components: an adsorber

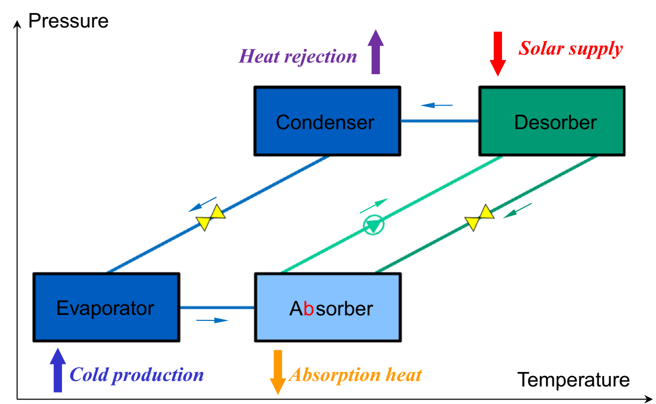


Fig. 3. Basic absorption refrigeration cycle.

that operates also as a desorber in charging mode, and a condenser that operates also as an evaporator in discharging mode. A continuous process requires simultaneously four components (Fig. 4) that operates alternately.

The common working pairs in field of solar machines are silicagel/H_2O and activated carbon/methanol, whose regeneration (desorption) temperature are easier to be achieved by cost effective flat-type solar collectors than regeneration temperatures of liquid sorbents.

Due to the fact that the solar refrigerators encountered in Africa are mostly intermittent sorption ice makers (see Section 3), their operating principle and common design are described in detail in Fig. 5. The machine consists of three main components (Fig. 5):

- a combined solar collector/adsorber that contains the adsorbent bed;
- a condenser, usually an air-cooled fin type heat exchanger that is cooled by natural convection;
- an evaporator located in a cold cabinet that is well insulated.

From the operating principle, it can be noticed that sorption ice makers are operated under 4 boundary temperatures, on the contrary to common sorption refrigeration machines, which are 3 temperatures cycles.

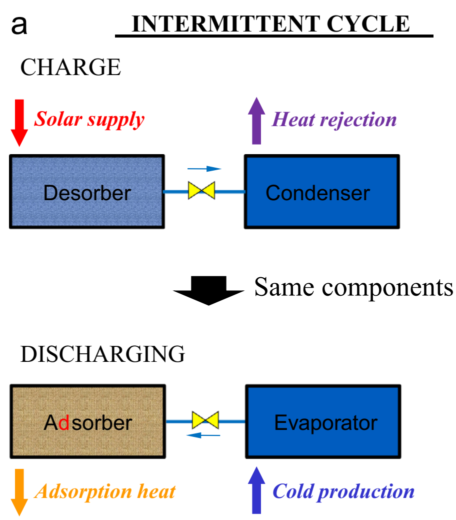


Fig. 4. Basic adsorption refrigeration cycle.

2.1.3. Desiccant cooling technology

Desiccant cooling cycles are open cycles that use the moisture or water vapour contained in the air as refrigerant. Simply, it could be said that a desiccant cooling process is an improvement of the classical evaporative cooler where the sorbent (solid or liquid) is used to dehumidify incoming air in order to remove its latent heat and increase its humidification potential; therefore the corresponding cooling effect that could be created is increased. Solar energy is used to regenerate the wet sorbent, which is carried out in a rotating wheel for a continuous process in the case of an adsorbent (usually the silica gel). Another possible benefit of sorption dehumidification is the ability to remove inorganic and organic contaminants in the air as well as biological pollutants such as bacteria, fungi and viruses, hence improving indoor air quality [9].

The operating principle of a solid desiccant cooling process is described in Fig. 6. Fresh air is blown through a sorbent contained in a rotative wheel (Fig. 6, point 1). Dry and hot air exits (point 2) the sorbent bed as the humidity is adsorbed by the sorbent and the temperature increases due to adsorption heat. The hot air is cooled (Fig. 6, stage 2–3) in a heat exchanger before it enters a humidifier, in order to adjust the humidity to a level of comfort (Fig. 6, stage 3–4). The corresponding evaporative cooling effect decreases further the temperature of the air that is blown in the building in a cool and dry state.

The warm and humid exhaust air from the building (point 6) enters a humidifier and is brought near to saturation (point 7), in order to maximise its cooling potential. Then, it exchanges heat with the incoming air (Fig. 6, stage 7–8) before it receives solar heat (Fig. 6, 8–9). Finally, the hot air removes humidity from the sorbent bed, thus regenerating the sorbent bed (Fig. 6, stage 9–10).

Actually, the inlet air (1) may be taken either from outside or from the cooled space, depending on the ambient conditions. A desiccant cooling system provides more cooling power than simple evaporative cooling system but its electricity consumption is higher and it requires thermal energy for the regeneration of the desiccant.

2.2. Elements of comparison of solar sorption refrigeration technologies

2.2.1. Short overview of predominant climatic zones in Africa

Located between latitudes 37° north and 35° south, Africa is the most tropical [11] of the continents. Since the performance of solar refrigeration applications are strongly dependant to the ambient conditions, the main climates encountered in Africa are briefly presented here, mainly based on Refs. [10–12]. Significant regional variations exist within each of the following depicted zones. The 6 major climatic zones, which are almost symmetrically arranged on both side of the equator, are depicted in Fig. 7:

Equatorial climate: it is characterised by a very regular temperature pattern year-round. All over the year, temperatures are high and mostly remain above 21 °C, with an average annual temperature of about 25 °C. Thus, daily and annual temperature variations are very low.

Tropical wet and dry: annual temperature variations are slightly higher than in equatorial climate zone.

Semi-arid: in this hot steppe zone, the average diurnal temperatures range from 25–36 °C and the short rainy lasts 1 to 3 months.

Arid or desert: the diurnal and annual temperature variations are very extreme, with temperatures below 0 °C and above 50 °C in the Sahara, depending on the period of the year.

Mediterranean climate: these regions have mild and rainy winters followed by a prolonged sunny, warm and dry summers when the temperatures are moderate (mid-20 °C).

Highland climate: the topography greatly modifies the climate here with temperatures average of 16 to 21 °C.

2.2.2. Comparison of solar refrigeration technologies

Table 1 gives some key features of solar sorption refrigeration processes. The prices that are shown in Table 1 are indicative since they are obviously dependent on the product. For sure, a solar SR requires far higher investment than a conventional compression cycle; it usually requires a cooling tower for continuous operating. The high cost of solar sorption refrigeration technologies is currently the main obstacle for the diffusion of technology.

Adsorption machines are quite bulky, with a significant amount of material and large size exchangers; they are expensive, compared to absorption machines. However, the regeneration temperature level that they require is easier to reach than that required by the liquid sorbents for efficient operation. Adsorption machines usually require no or reduced moving parts, therefore reducing the need of maintenance. This is very important in a context where many projects fail because of lack of maintenance due to non-locally manufactured parts, the scarcity or lack of skilled technicians for a particular plant.

Another important parameter, usually used as a performance indicator is the solar COP. The thermal COP in Table 1 corresponds

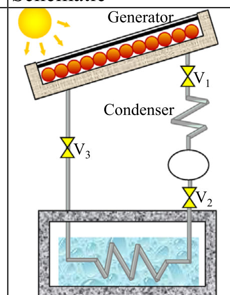
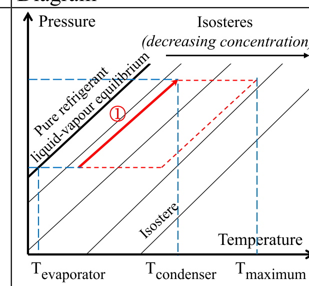
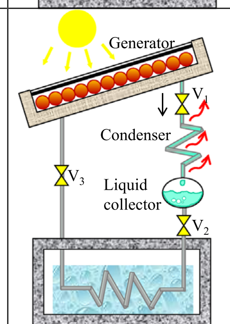
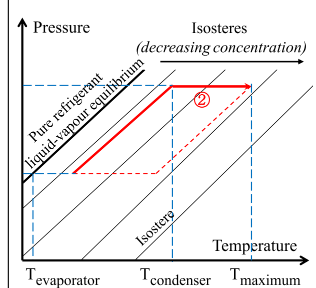
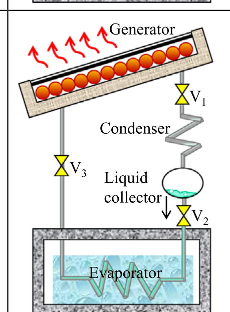
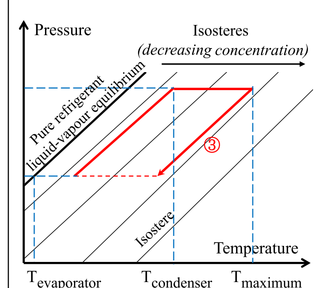
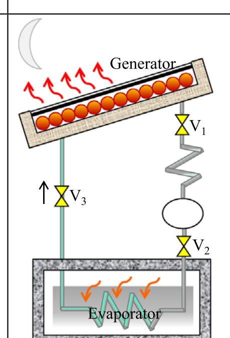
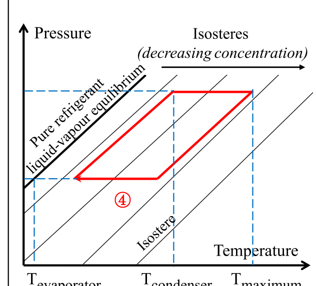
Phase	Description	Schematic	Diagram
① Initial isosteric heat-up (Sunrise[a])	Solar energy heats the adsorbent, which is fully loaded with the refrigerant, from the ambient temperature up to a maximum cycle temperature and pressure. All the valves ($V_{1\text{-}3}$) remains closed during this phase.		
② Desorption-condensation (10 a.m.–1 p.m.)	When the saturation pressure corresponding to the condenser temperature (approximately) is reached in the generator, V_1 is opened. The refrigerant flows into the condenser where it condenses to liquid phase. The liquid flows by gravity into a liquid collector or directly into the evaporator. The condensation heat removal is usually insured by natural convection. Desorption-condensation continues until desorption is assumed almost complete.		
③ Isosteric cool down (1–7 p.m)	When no significant generation of the adsorbent is noticeable, V_1 is closed. As the solar insolation decreases or eventually the refrigerator is prevented from further solar insolation, the adsorbent cools down close to the surrounding temperature. This cooling could be enhanced by the removal of the collector glazing or other insulation or covers. Thus, the temperature and pressure in the generator decreases. This is the isosteric cooling down phase.		
④ Adsorption – cold production (After 7 p.m.)	When the pressure of the adsorber is low enough (below the saturation vapour pressure of the refrigerant), the evaporator and the adsorber are connected by opening V_3[b] and the adsorbent can adsorb the refrigerant. This yields in an evaporation that produces a cooling effect. A water bath in which the evaporator is immersed cools down or even freezes. Because adsorption is an exothermic phenomenon, the performance depends on the cooling of the generator at night-time (natural convection); this heat removal can be supported by the night sky radiation between the generator and the ambient. When the adsorbent becomes saturated, the refrigerator cycle is complete.		

Fig. 5. Operating principle of an adsorption icemaker (common design). [a]The duration of each step depends on the meteorological conditions and the given time indications are only indicative. [b]If there is a liquid receiver with valve V_2, the latter is opened in order to feed the evaporator with the refrigerant prior to the opening of V_3.

to the ratio of cooling energy to the heat supplied to the generator (desorption process). The solar COP corresponds to the ratio of cooling energy to the incident solar insolation. It appears that the solar COP of sorption processes, mainly the adsorption one is relatively low (Table 1).

Desiccant cooling cycles are mostly used in North Africa (see Section 3), while open sorption cycles are mainly used for drying or dehumidification applications in sub-Saharan areas [13–16]. In hot-humid climates or high humidity of ambient air, which is the case in equatorial climate and coastal areas of the Mediterranean region, a special and more complex design of the desiccant cooling process is required in order to reduce the high humidity to a sufficiently low level for a direct use with an evaporative cooling [17]. The basic design of desiccant cooling in hot and humid climates might even require more energy than a conventional vapour compression cycle of same power [18,19].

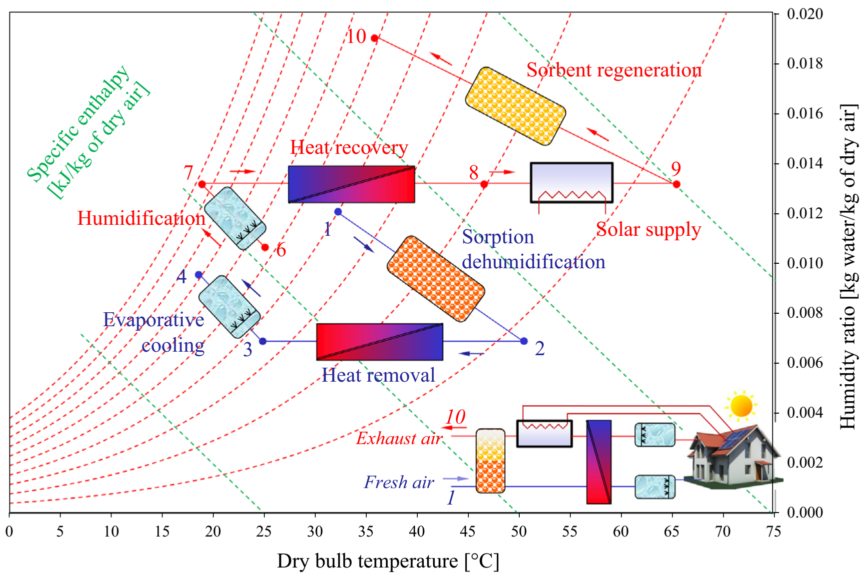


Fig. 6. Basic dessicant cooling cycle.

Sorption refrigeration machines, particularly absorption machines, are commercially available power for large power applications (Table 1). However, small power (5–10 kW) absorption units market is currently developing [20].

3. Research activities and demonstration projects

The following section describes country by country, applied research activities and projects of solar sorption refrigeration in Africa. The named cities in the paper are indicated on the map in Fig. 7.

3.1. Nigeria

The research work on solar refrigeration conducted together by the Centre for Energy Research and Development (University of Nigeria, Nsukka: UNN, latitude 6.9°N) and the Federal University of Technology of Owerri (Nigeria, latitude 5.9°N) is one of the most long-term and sustained of this field in Africa, over three decades [21–32]. These activities focused mainly on the development of an adsorption solar refrigerator using as much as possible locally available materials. Prototypes of two different solar SRs have been designed, constructed and tested.

The first one employs $CaCl_2/NH_3$ as working pair [29]. $CaSO_4$ and cement have been mixed with the $CaCl_2$ in order to obtain a more stable adsorbent [29]. The adsorbent was installed in a combined collector/adsorber/generator unit that has an overall collector plate exposed area of 1.41 m^2. A stagnant water evaporative condenser made of reinforced sandcrete and a spirally coiled evaporator were installed directly under the adsorber. An effective cooling, which is equivalent to an ice production of 1 kg day^{-1} m^{-2} of solar collector was achieved [29]. A further development of the adsorbent, the so called “Nsukkanut”, has been conducted in order to handle some problems of the material (swelling, compacting, disintegration, low efficient thermal conductivity, etc.) when maintaining a sufficient porosity [21]. Therefore, various thermophysical properties of the “Nsukkanut” have been deeply studied [23,24]. The new adsorbent has been used in the original prototype for long-term performance measurements [22]. After more than 40 tests over the annual climatic variations at Nsukka, no reduction in the performance of the unit was observed. The highest daily performance of a prototype with 1.41 m^2 collector was a useful cooling and ice production of 0.833 MJ m^{-2} and 1.65 kg m^{-2}, respectively [22]. The solar COP varied over 0.008–0.053, which is low considering that solar COP of 0.1 or more are possible for solar powered adsorption refrigerators (AdSRs). The most recently reported activity regarding the $CaCl_2/NH_3$ considers a theoretical analysis of the heat and mass transfer in porous spherical pellets [33]. Among other things, it is reported that the intra-pellet free ammonia diffusion resistance and temperature are not significant for $CaCl_2$ pellet diameter ranging from 4 to 20 mm [33].

Later on, a similar solar SR, using this time activated carbon/methanol as working pair, has been investigated at the UNN. A prototype was designed, constructed and tested. Some features related to the constructed prototype are given in Table 2. The researchers have selected the activated carbon/methanol working pair for numerous advantages that it offers [28]: inexpensive material easily available or producible in most developing countries, relatively easy construction because of low pressure operation conditions, chemical stability, enhanced COP. The refrigerator consisted of three main components (Figs. 8a, 9, and Table 2) [26,31]:

- A combined solar collector/generator/absorber with 6 collector tubes, each of which consisting of two co-axial tubes installed in a flat type collector (Fig. 8b). Activated carbon is packed in the annular space between the inner and outer tube. The inner tubes are regularly perforated in order to favour desorption/adsorption of the methanol (the inner tubes collect or distribute the methanol).
- An evaporative type condenser, consisting of a steel tube coil with a square plan view, submerged in a pool of stagnant water contained in a reinforced 350 l sandcrete water tank; the latter tank operates as a pot-in-pot refrigerator to keep the water inside cooler.
- An evaporator made of a spirally coiled copper tube immersed in a 3 l of water contained in an insulated steel vessel.

The operating principle of the refrigerator [31] is similar to the description given in Section 2.1.2. The performances of the constructed solar SR at the UNN are presented in Table 2. Additional activities deal with various transient simulation models [31,32], which have been used in order to predict the performance of the refrigerator and avoid costly experiments. These models have been

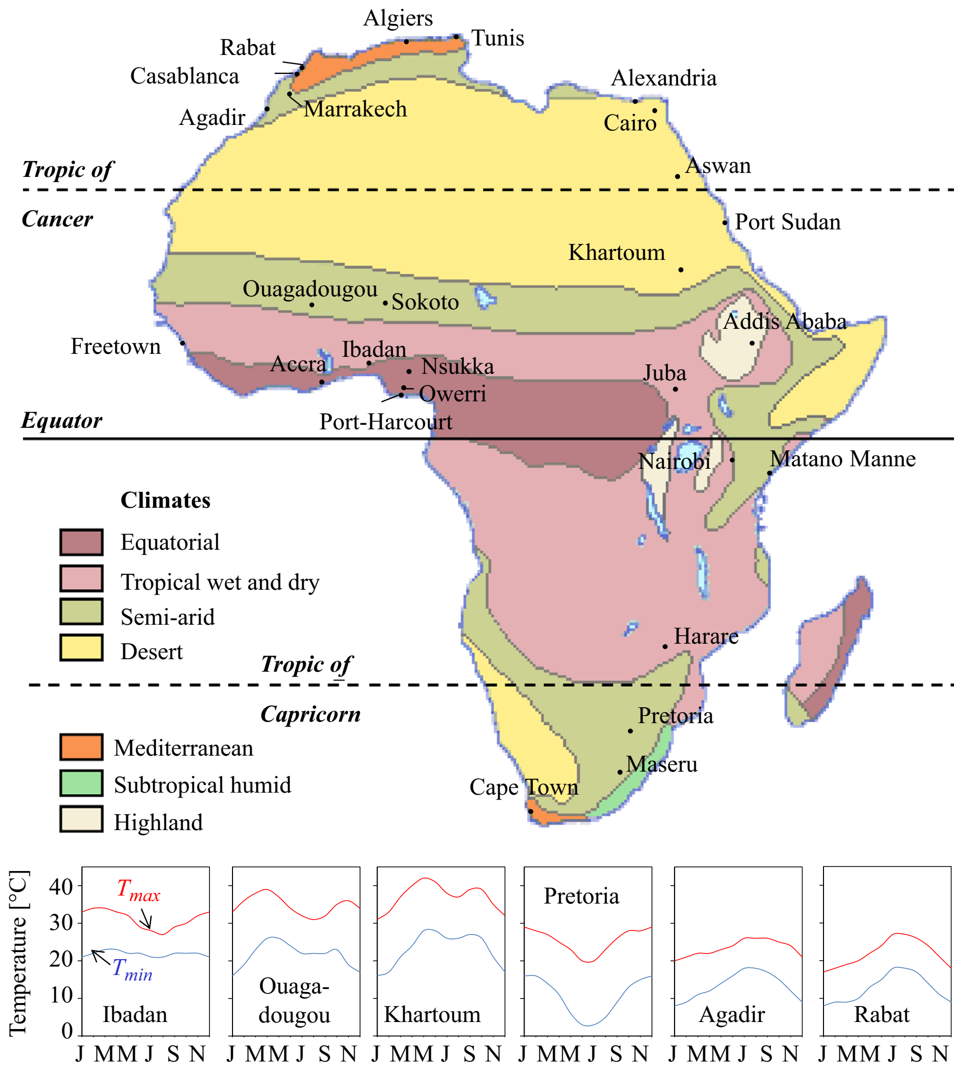


Fig. 7. Main climatic zones in Africa.

Table 1
Comparison of solar refrigeration technologies. The given data are only basic indications.

	Absorption	Adsorption	Desiccation
Cost	+200–600 € kW^{-1}	++200–600 € kW^{-1}	++
Maintenance	++	+ (usually without moving parts)	++
Capacity	20–5000 kW	1–500 kW	20–300 kW
Life time	15 years	25 years	–
Electrical auxiliaries consumption	++	+(eventually no one)	++
Regeneration temperature	75–120 °C	50–100 °C	45–90°C
Thermal COP	0.4–0.75 (single effect) 1–1.3 (double effect)	0.3–0.7	0.6–0.75
Solar COP	0.07–0.3	0.05–0.15	–
Safety	Risk of crystallisation depending on the working pair	No crystallisation problem	Possible crystallisation problem if liquid sorbent
Operation	Constant cooling power under constant boundary conditions.	More binding due to the cyclic operation. Decreasing cooling power during operation under constant boundary conditions.	A lot of components require a challenging control.
Bulk	+	++	++
Pressure range	0.01–20 bar	Atmospheric	Few mbar
State of the art	Some products on the market	At early stage of development	Mature technology

[a]Small power (5 to 10 kW) absorption units market is currently developing [20]: Climatewell (4–10 kW), Rotartica (4.5 kW), Sonnenklima (10 kW), ROBUR, etc.

satisfactory validated and used for the optimisation and improvement of the refrigerator, mainly the combined collector/generator/adsorber [32].

Theoretical thermodynamic analysis of adsorption machines, considering common solid adsorbents, namely activated carbon/methanol, activated carbon/ammonia and zeolite/water, has also

Table 2
Main components and performance of the some of the reviewed solar SR in Africa.

Location	Technology	Working pair	Collector/generator	Condenser	Evaporator	Cold cabinet	Performance	Ref.
Nsukka, Nigeria	SAdIM	Activated carbon/ methanol	Plate collector Effective area: 1.2 m^2 Tilt angle: 7° 6 collector tubes Outer tube diameter: 60.3/52.5 mm Inner tube with perforation:21.3/ 15.8 mm Tube length: 1.64 m Generator mass: 60 kg	Evaporative condenser installed in water bath Steel tube coil: Length: 4.78 m Diameter: 21.34/ 15.8 mm	Spirally coil Length: 1.62 m Diameter: 2.7/0.9 mm	Water tank content: 3 kg	Solar COP: 0.007–0.015 Cooling temperature: ~1 °C (only chilled water was produced) Generation period: 6.5–8 h Maximum generation temperature: ~96 °C Average ambient temperature: 22.2–34 °C	[26]
Ibadan (Nigeria)	SAdIM	Activated carbon/ Methanol	Effective area: 0.64 m^2 glazing: a sheet of glass (about 2mm) 8 copper tubes: Length: 0.700 m Insulation: 150 mm (thickness) fibre glass 3.79 kg of activated carbon	Evaporative condenser installed in water bath Copper tube Diameter: 25.4 mm Length:~3.0 m	Copper tube Diameter: 25.4 mm Length:~3.0 m	Available volume: for five 1 l container Insulation: 100 mm of fibre glass covered by 3mm of white Perspex	Solar COP: 0.025 (best) Air leakage problems	[36]
Agadir, Morocco	SAdIM	Activated carbon/ methanol	Area: 1 m^2 Tilt angle: 20° Maxsorb selective surface Air cooled condenser with fins (7.5 m^2) integrated into the generator 20 kg of activated carbon	Integrated to the generator	Steel Area: 0.3 m^2	Water tank of 5.2 l (ice container)	Solar COP: 0.12 Daily ice production: > 5 kg	[39]
Rabat, Morocco	SAdIM	Activated carbon/ methanol	Effective area : 0.73 m^2 Removable dampers 15 kg of activated carbon (AC35)	Air cooled fin condenser Copper tube: Diameter: 26/28 mm Length: 5.2 m Total fin area: 7.5 m^2	Copper pipe Diameter: 38/ 40 mm Total area: 0.61 m^2	Available volume: 113 l Insulation: 100 mm of glass wool	Solar COP: 0.02–0.08	[47–49]
Pretoria, South Africa	SAdR	Silicagel/water	Flat plate collector Tilt angle: 30° Effective area: 1.6 m^2 25 tubes Diameter: 42/39 mm Length: 1240 mm 30 kg of silica gel	Air-cooled condenser by natural convection Copper pipe: Diameter: 22 mm Length: 7.15 m Aluminium fins: 2 m^2	Copper pipe Diameter: 54/ 51 mm Length: 7 m Total area: 1.2 m^2	Water tank of 25 l (ice container) Available volume: 216 l Insulation: 100 mm of Energylite	Solar COP:0.058 Chilled water (6–15 °C) was produced but significant temperature raise during daytime Air leakage problems	[61]
Kenya	SabIM	H_2O/NH_3	Parabolic trough solar collector Total area: 11.9 m^2 81.8 kg of water (absorbent) 70.9 kg of ammonia (absorbate) Pressure: up to 16.5 bar	–	–	50 kg of ice container	Up to 50 kg per sunny day. (about 5 kg m^{-2})	[70,71]
Ouaga-dougou, Burkina Faso	SAdIM	Activated carbon/ methanol	Single-glazed flat-plate selective solar collector Total area: 2 m^2 Tilt angle: 14.2° 12 tubes Diameter 70 mm thickness 1 mm Selective layer (Maxorb) Absorptance: 0.9, Emissivity: 0.10–0.15 Central tube (metal grid) diameter: 10 mm Insulation: 30 mm glass-wool 40 kg of Acticarbone AC40 (CECA)	Air cooled condenser with external fins Total fin area: 6 m^2 Length: 2 m	Diameter: 50 mm Total area: 1.7 m^2	Water tank of 40 l (ice container) Available volume 440 l Insulation: 150 mm of expanded Polystyrene	Solar COP: 0.09–0.13, (insolation: 19–25 MJ m^{-2}; average temperature: sunrise: 27.4 °C, mid-afternoon: 37.4 °C).	[76]

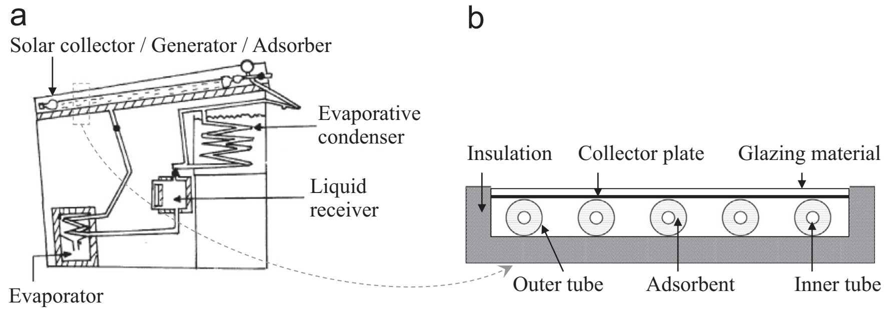


Fig. 8. (a) Schematic of the second SAdIM built at the UNN [25] with (b) details of the collector/generator/adsorber [31].

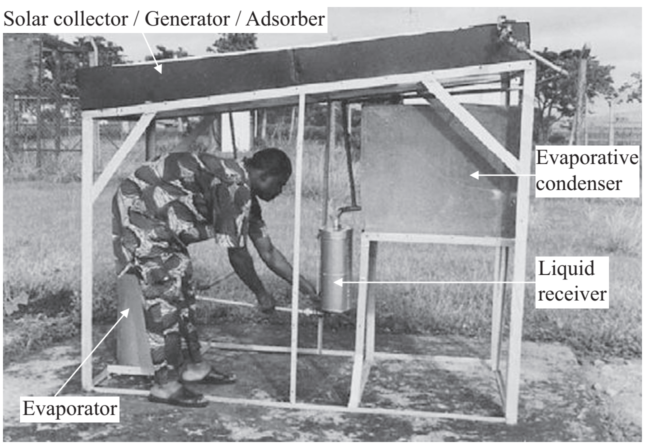


Fig. 9. Photograph of the solar refrigerator built at the UNN [26].

been reported by Anyanwu [30]. He has shown that the maximum possible solar COPs for these working pair are 0.3, 0.19 and 0.16, when a conventional flat plate solar collector is used. It also appears that zeolite/water is the best working pair for air conditioning application while activated carbon/ammonia is preferred for ice making, deep freezing and food preservation [30].

More recently, with the increased interest for the composites based on salt hydrates in adsorption refrigeration machines, eleven adsorption working pairs have been investigated at the Federal University of Technology, Akure (Nigeria, latitude 7.3°N) [34]. The adsorption capacities of ammonia on various $CaCl_2$ composites ($CaCl_2$–Charcoal, $CaCl_2$–Silica gel and $CaCl_2$–$CaSO_4$) have been measured. An adsorbent made of 25% $CaCl_2$ and 75% silica gel had shown the highest value of adsorption capacity (68 $cm^3\,g^{-1}$ at 40 °C).

In 1995, Iloje and Enibe [5,35] have prospected the ability of an AdSR to produce cold at various periods in the year and this, for 15 African cities over the climatic zones in Africa. They used a model of a refrigerator that operates with $CaCl_2/NH_3$ under monthly average daily insolation and ambient temperature values. Therefore, the obtained performances (available cooling per day) are only indicative since they are sensitive to solar insolation and ambient temperature, and the available meteorological data where mainly monthly averages. The simulation suggested that in Africa, the Mediterranean climate offers the highest potential for solar cooling, and this in summer, because of the high insolation (25–32 $MJ\,m^{-2}$) and moderate ambient temperatures (20–24 °C). So, Tunis and Algiers (northern Mediterranean) indicate the highest available cooling per day in June (northern summer) as well as Maseru (South Africa, southern Mediterranean, 29.3°S) in December. On the contrary, low performances are observed for the tropical forest region (e.g. Accra, Freetown, Port Harcourt) where the weather is cloudy over most of the year (low insolation) while the ambient temperature remains fairly high. In the desert and northern arid belt (Aswan, Port Sudan, Khartoum, Sokoto), where insolation and ambient temperature are high, the performances are moderate to high the year round, except in December. Although the above results are mainly obtained from monthly averages meteorological data, they are a good starting point for performance prediction and comparison of various African regions.

A very recent study at University of Ibadan aims to evaluate the workability of an activated carbon/methanol working pair and to determine the solar COP of a refrigerator based on this pair [36]. The activated carbon used is prepared from olive stones, which are waste by-product with significant amounts in the oil industry. The refrigerator (Fig. 10, Table 2) was tested in November 2012. For one of the reported tests, the average condensation temperature was 39 °C and the maximum temperature in the adsorber was 98 °C under a daily average solar radiation of 500 $W\,m^{-2}$. The adsorption of methanol seems to be very heterogenous in the adsorber so that not the whole adsorbent could be moisted. The best solar COP was as low as 0.025. This very low performance was attributed, among other things, to air leaking into the system. The results confirm the suitability of the activated carbon/methanol pair for use in an intermittent solid adsorption cycle. The authors recommended not exceeding 150 °C when using methanol in order to avoid formation of other compounds that could slow the kinetics of evaporation.

3.2. Morocco

Boubakri et al. [37–40] have developed for several years a SAdIM using activated carbon (Fig. 11, Table 2). The experimental tests have been carried for a long time in Agadir (latitude 30.4°N, south of Morocco, summer 1990), where the Mediterranean climate reveals relatively favourable for solar ice makers [39]: yearly average insolation (19.54 $MJ\,m^{-2}$), ambient temperature during daytime (24 °C) and night-time (15 °C). This is in accordance with simulations performed by Le Pierrès [41] for a low temperature solar refrigerator in Casablanca (latitude 33.3°N, Morocco). The main new feature of the proposed unit is the fact that the solar collector and the condenser are assembled as a single component (Fig. 10) [37–40]. Fins located at the rear surface of the collector insure condensation of the refrigerant. Activated carbon/methanol is used as the working pair. A daily ice production of more than 5 kg and a solar COP of 0.12 were achieved. The machine got into the market in the 80s by Brissoneau et Lotz-Marine (BLM), a French company which has however stopped the production because the product was too expensive (US$ 1500 for a daily ice production equal to 5.5 kg.by late 80s [42]). A new design of the machine shows a single heat exchanger playing alternatively the role of condenser and evaporator [40,43]. It is expected that this new design would result in a better performance of the machine while reducing simultaneously its weight and the cost.

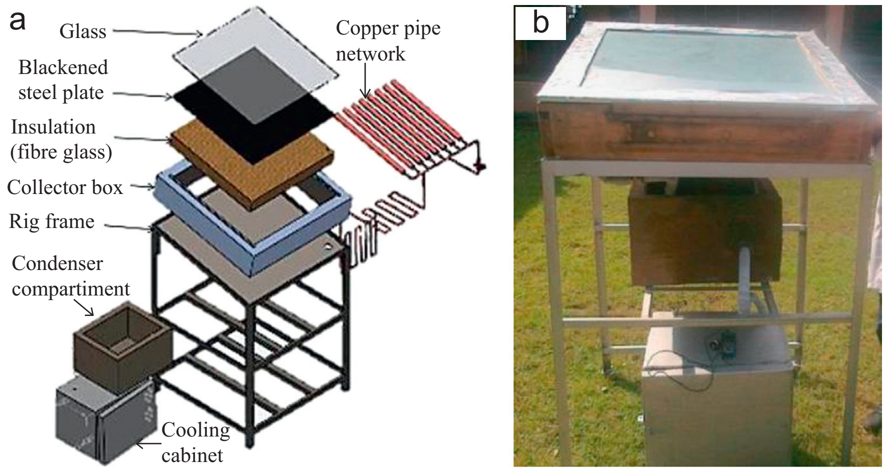


Fig. 10. Photograph of the adsorptive solar powered refrigerator in Ibadan (Nigeria) [36].

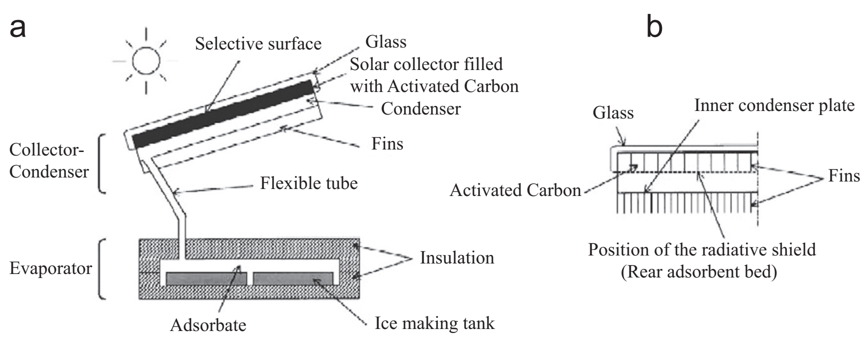


Fig. 11. Schematic of the collector–condenser ice maker technology [39].

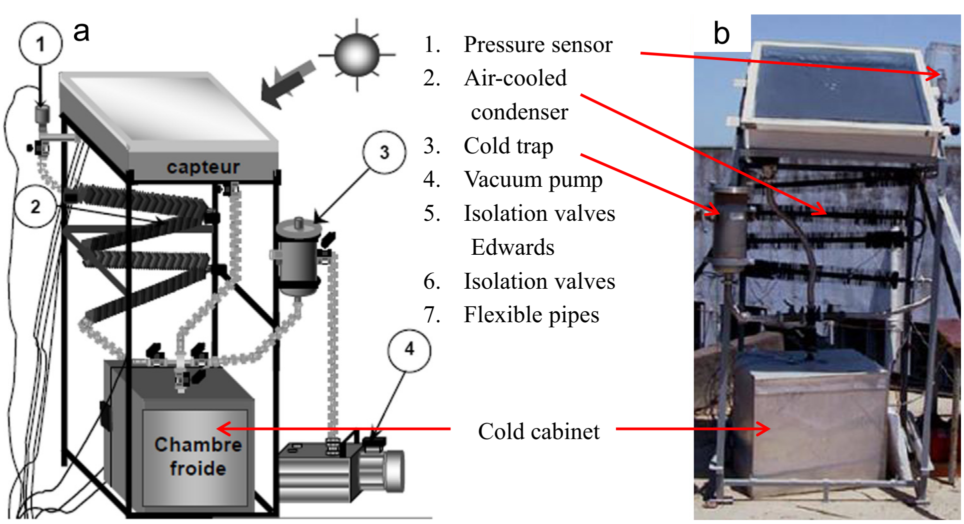


Fig. 12. Photograph of the SAdiM developed by Errougani et al. [48].

Lemmini et al. [44–49] have investigated an AdSR with the AC/methanol working pair at the University Mohammed V – Agdal in Rabat (latitude 34.0°N). Year round performed simulations using two different AC, namely AC35 and AC40, show that in Rabat (Mediterranean climate), the best efficiency of the machine is achieved in winter [45]. They also indicate that AC40 leads to 20% better performance than the AC35 on days with low insolation. Further simulations have been performed in order to compare the performance of the AdSR in two different Moroccan cities: Rabat (temperate and humid climate) and Marrakech (hot and dry climate) [44,46]. Though the annual cold production for both cities is similar, the distribution of underachievement days is completely different [44]. In Rabat, deficits are due to successive little sunshine days while in Marrakech, high ambient temperature values for much of the year reduce the performances. Following these theoretical works, an AdSR, using AC_{35}/methanol has been built and tested in 2003–2004 [47–49]. The machine was completely designed and built (Fig. 12) using locally available materials (Table 2) [48]. The rear and the side of the collector are covered with dampers and this improves the heat supply during desorption. However, the dampers have to be removed during the

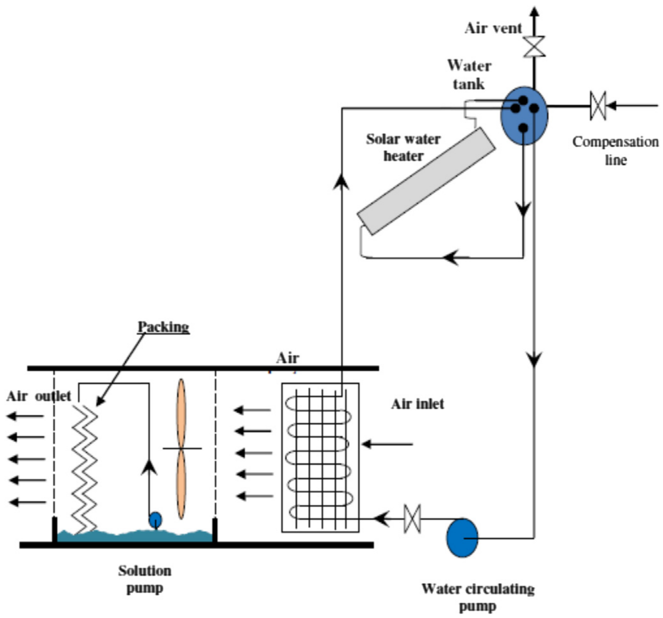


Fig. 13. Schematic diagram of a desiccant regenerator investigated by Alosaimy et al. [55].

adsorption phase to allow efficient cooling. They authors used copper as main metallic component because it has good heat conduction properties and also because of technical constraints related to the tightness of the process, which operates under vacuum. A first collector design reveals not to be tight [48]. To reduce the risk of inward leakage, silver has been used for the welding and the number of welding points was limited by the selection of an appropriate implementation. Then, temperatures down to −11 °C have been measured and even on rainy and cloudy days, significant cold is produced. However, the temperature in the evaporator may fluctuate daily up to 20 °C. The solar COP ranges from 0.02 to 0.08 [48] and is higher than 0.05 for an insolation higher than 24 MJ m^{-2}.

3.3. Egypt

Due to its favourable solar potential – average solar insolation average of solar radiation ranging between 20 and 30 MJ m^{-2} day^{-1} from the north to the south [3] – numerous studies [3,4,50–59] of SR technologies have been carried in Egypt. An economical comparison between a solar powered absorption air conditioning system and a vapour compression system considering the heat load of a five-floor hospital in the hot and humid summer climate of Alexandria City (Mediterranean coast of Egypt, latitude 31.2°N) showed that the double-effect solar air-conditioning system is recommended for use in such applications [3]. Indeed, the later has been proved to be economically worthier than a vapour compression unit, what is not the case of a single effect solar air conditioning system.

Intensive research activities on absorption desiccant cooling [51–56] have been carried at the Faculty of Engineering of Mansoura University (latitude 31.0°N) in collaboration with Taif University (Saudi Arabia, latitude 21.3°N). Basically, $CaCl_2$ aqueous solution is used as desiccant as it is in the case of other studies in Egypt [58–60]. Recent activities concentrate on the use of artificial neural network (ANN) technique in the performance evaluation of absorption desiccant cooling [54–56]. For instance, the regeneration of $CaCl_2$ solution using a solar water heater coupled with a commercially available evaporative air cooler (humidifier) has been investigated based on an experimental plant in Taif University, using ANN [55]. Ambient air is heated by solar energy, which is stored in water tank. The hot air is blown through the humidifier where it removes water from the desiccant (Fig. 13); therefore, the humidifier behaves as a solution regenerator. The experimental results show that the unit can operate at nearly steady state condition when a storage tank is applied with the solar collector, with the ability to regenerate $CaCl_2$ from 30% to about 50% (mass fraction). An ANN that has been developed to predict the overall performance of the system provides results that are in good agreement with the experimental results [55]. Another specificity of the research activities at Mansoura University was the focus on the use of a solid porous bed carrying a liquid desiccant in a stationary bed [52,53]. Porous granules of burned clay were impregnated with $CaCl_2$ solution. This offers the advantage of a stationary bed operation without the need of an apparatus in which a continuous circulation of liquid solution is carried out.

Bassuoni [57] reported an experimental study of a packing dehumidifier/generator operating with liquid desiccant at Tanta University. The author studied the performance of a cross flow dehumidifier/generator addressing the effects of main operating parameters on a labscale test rig (Fig. 14), the life cycle cost analysis with comparison with vapour compression dehumidification system and a life cycle analysis (LCA). The overall environmental impacts of the desiccant cooling system were found to be nearly 0.63 of that of a vapour compression system. The payback period of the desiccant cooling system is evaluated to be 11 months with annual running cost savings of about 31.2% compared to vapour compression system dehumidification.

Hassan and Hassan [58] considered the improvement of $CaCl_2$ solution, a cheap desiccant, which is however unstable. Therefore, the aim of the study was to achieve a cheap liquid desiccant with better stability. The authors mixed $CaCl_2$ aqueous solution with $CaNO_3$ aqueous solution in different weight combinations in order to find the mixture that fulfils higher air dehumidification, based on vapour pressure measurements. The best liquid desiccant was found to be a mixture of $CaCl_2$ aqueous solution of 50% of weight concentration with $CaNO_3$ aqueous solution of 20%. Thermophysical properties (density, viscosity, vapour pressure) of the proposed desiccant have been measured and reported.

Khattab [50] investigated a labscale SAdIM consisting of a circular container (adsorber) and a combined evaporator and condenser (Fig. 15). The desorption heat is supplied using a simple arrangement of plane reflectors and the desorber is maintained above 100 °C more than 5 h a day. Various adsorber beds and reflectors configurations have been tested in Cairo (latitude 30°N). The use of a circular container for the adsorber bed instead of tubes aims at increasing the exposed area to the sun and favour uniform temperature distribution in the bed. A cheap activated carbon (domestic charcoal) was used with methanol as working pair. The author reported very promising performances as good as a daily ice production of 6.9 and 9.4 kg m^{-2} and a solar COP of 0.136 and 0.159 for winter and summer climate respectively. The maximum attained temperature in the desorber is 133 °C, which is still below the dissociation temperature of methanol (150 °C) [5,36].

3.4. South Africa

A solar refrigerator was designed (Table 2), built (Fig. 16) and tested in 2007–2008 at the Tshwane University of Technology in South Africa [61]. The selected working pair is silicagel/H_2O for its relatively low regeneration temperature (80–100 °C). The complete design of the system components (Table 2) is detailed by Nwamba [61]. For an average ambient natural cooling condensing temperature of 35 °C, chilled water (6–15 °C) is delivered by the refrigerator. However, the temperature of the cold cabinet increases beyond 10 °C and up to 35 °C during the day, deserving

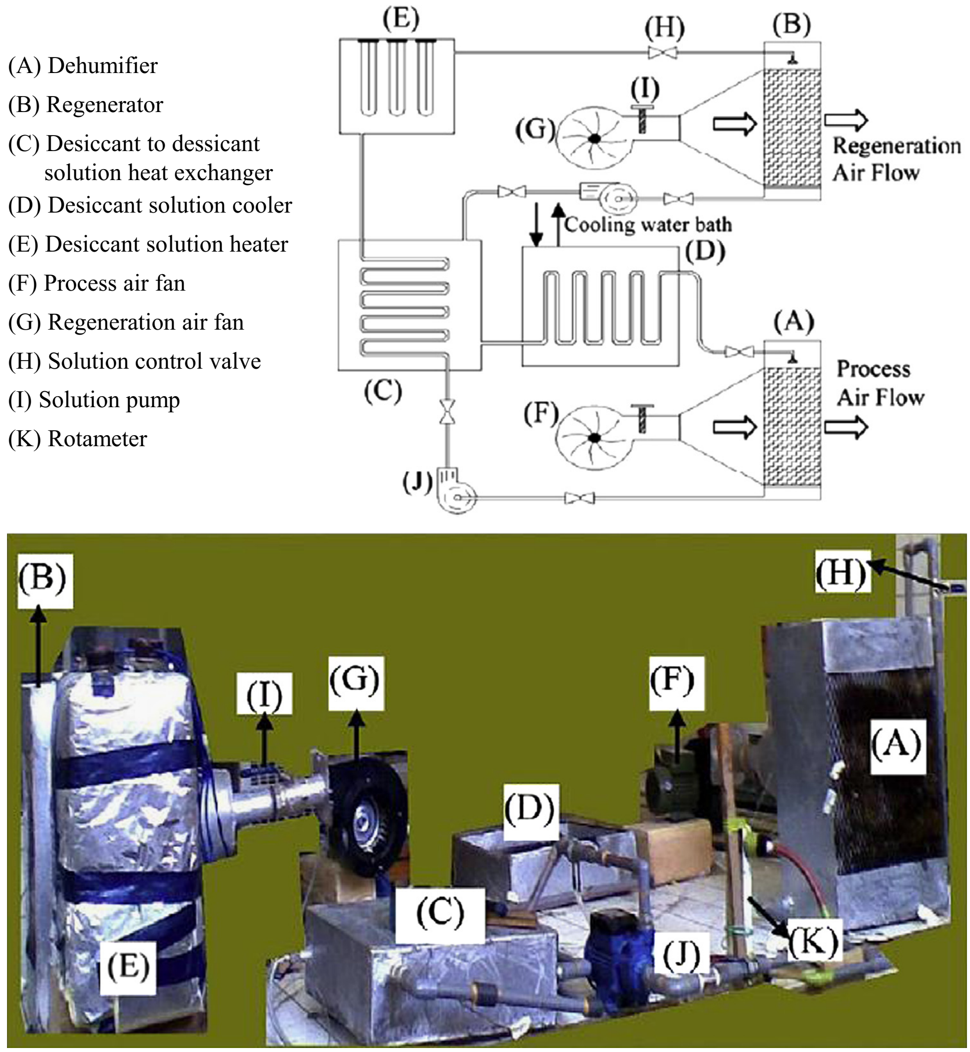


Fig. 14. Schematic diagram and photograph of a cross flow liquid desiccant dehumidification system investigated at Tanta University (Egypt) [57].

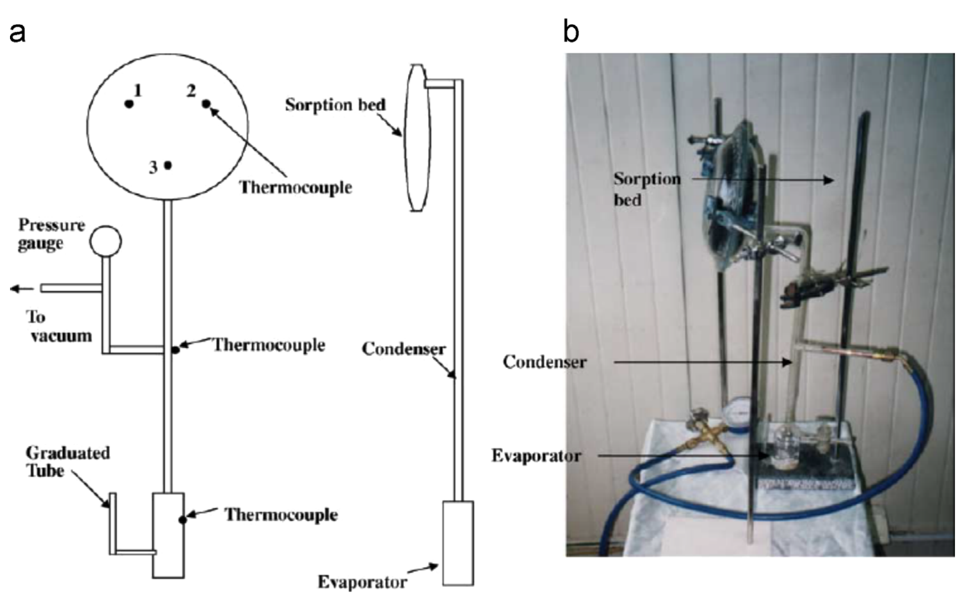


Fig. 15. Schematic and proposed module of SAdIM by Khattab: (a) modified glass tube (b) photograph of the modified glass tube [50].

the target of the machine, which was vegetables and fruits preservation (4–10 °C). This underachievement was attributed to various factors, mainly an insufficient insulation of the cold cabinet and air inward leakage into the process (up to 50 mbar after five operation days). The latter is known to be very prejudicial to sorption processes, as reported by Kreussler et al. [62]

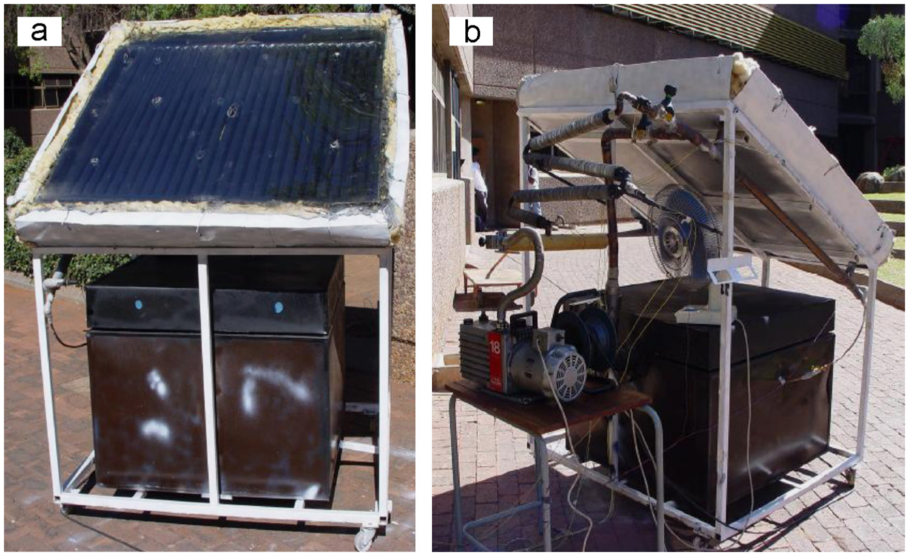


Fig. 16. Photograph of the solar powered adsorption refrigerator at the Tshwane University of Technology: (a) front and (b) rear view (South Africa) [61].

who dealt with a solar refrigerator using zeolite/H_2O for developing countries. A low solar COP of 0.058 was achieved. The cost of the solar refrigerator was estimated higher than 3600€. The author estimated that the cost could be much higher since a skilled labour and vacuum technology is necessary. The study also made an economic comparison between solar assisted refrigeration and a conventional fridge to pave the way for future studies.

A car air conditioning based on absorption refrigeration has been investigated at the University of Cape Town [63]. Actually, this study is not specifically a solar application but it can inspire a solar one. The authors suggest an alternative to R-134a (often used refrigerant in car air conditioning) with lower global warming potential (GWP) refrigerant, while recovering the waste heat in the exhaust gas (typically the third of the available energy of the combustion fuel [63]). The system uses heat extracted from the exhaust gas of an internal combustion engine to power an absorption refrigeration cycle to air conditioning an ordinary passenger car [63]. H_2O/NH_3 was selected as absorption pair. Since NH_3 could not be used in an evaporator in direct contact with the users (toxicity regulation), a secondary heat transfer fluid (water or glycol) between the evaporator and the passengers space was used. After successful laboratory tests, road-tests to air condition the passenger space of a Nissan 1400 truck have been conducted. The results indicate a sufficient cooling effect – up to 2 kW – but a low COP (0.09), which is to be improved.

3.5. Sudan

This is one of the first large scale plants in Africa. A continuous single stage NH_3/H_2O absorption refrigerator was installed in Khartoum (Sudan) in the framework of a technical cooperation between the Sudanese and Dutch governments. The machine provides a peak cooling power of 13 kW for 10 t of agricultural products that have to be maintained below 5 °C in a 50 m^3 store. The circulation pump was electrically driven and the system operated satisfactorily during 9 months [64] and even for 6 years [64,65]. The average solar COP was about 0.096. However, the estimated total system cost (US$ 95000, cost in 1987) was too expensive for the target purpose. It was shown that the solar-driven absorption refrigerator could be competitive with the conventional compression refrigeration cycle only when the price of electricity was increased by a factor of ten.

Ahmed et al. [9,60,66] reported the performance of an internally cooled dehumidifier using triethylene glycol as a desiccant (Fig. 17). Exhaust air of an air conditioned space (faculty building) is blown at the bottom of a dehumidifier. This humid and warm upstream air flow is dehumidified by cold falling desiccant flow. It is further cooled in a fin tubes heat exchanger so that a cold air with an acceptable humidity level is blown in the air conditioned space. The cooling in the humidifier is provided through a cooling tower. An evacuated solar boiler was used for desiccant regeneration. The rate of humidity removal from the air was considered as the performance indicator of the process. The authors observed that the humidity removal rate increases with increasing the inlet air flow rate, inlet air humidity ratio, desiccant flow rate, and desiccant solution concentration in triethylene glycol.

Further theoretical works, such as a solar-driven liquid desiccant evaporative cooling system in Khartoum, have been reported by the same authors [67,68]. Among other things, they indicate that the investigated solar-driven liquid desiccant evaporative cooling can operate in humid as well as dry climates [67,68]. An application of the same process for banana ripening and cold storage has been also theoretically investigated by Abdalla et al. [69]. Banana ripening is a treatment process that requires maintaining a room air temperature between 20 °C and 25 °C under a relative humidity between 90% and 95%. The system proposed by the authors consists of ten main components and the operating principle would be long to be presented here (the reader is kindly invited to refer to Ref. [69] for complete details on the operating principle). Basically, a desiccant cooling process is used to produce nearly saturated cool air for banana ripening and cold storage. Solar heat is used for the regeneration of the desiccant. The simulations consider a reference case aiming at providing 23 °C (dry-bulb temperature) and 90% relative humidity air for indoor conditions, starting with an ambient air of 43 °C dry-bulb and 23.4 °C wet-bulb temperatures. As a result of the performed simulations, liquid desiccant evaporative cooling is suggested as the most cost appropriate for banana ripening and cold storage technology when compared to vapour compression or direct evaporative cooling in Khartoum [69].

3.6. Kenya

The Intermittent Solar Ammonia Absorption Cycle (ISAAC) was developed by Energy Concepts Company (Maryland, USA) for a dairy development NGO and its related communities in Kenya [70]. The project received the financial support of the World Bank

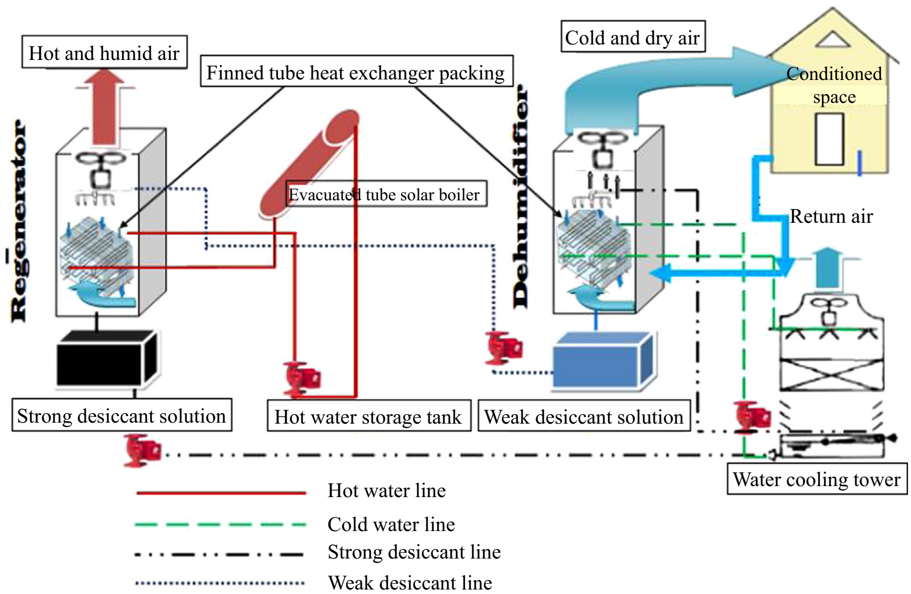


Fig. 17. Schematic diagram of a desiccant cooling system installed on at University of Khartoum–Sudan [51].

Fig. 18. Photograph of an ISAAC installed in Kenya [70].

in the framework of its Development Market place programme to support farmers of dairy cooperatives on the coast of Kenya [70]. The system is a solar absorption ice maker (SAbIM), using H_2O/NH_3 as working pair. It consists of a generator/absorber, a condenser and an evaporator (Table 2). The heat for regeneration is provided through stationary parabolic trough solar collectors (Fig. 18). Similarly to the AdSRs presented above, ISAAC operates in charging mode during the day and discharging mode in the night (Fig. 19). The generator is cooled by a thermosyphon. Alternating between the day mode and the night mode is operated with control valves on a control panel every morning and evening [70,71]. The vapour is partially condensed in a rectifier, increasing the ammonia purity before it is collected in the evaporator tank as ammonia refrigerant [71]. Construction of ISAAC requires only welding, piping and sheet metal work and only standard shop equipment [71]. A total of six units were installed in Kenya for dairy cooperatives and the project has generated about US$ 26,000 in five months (late 2008) [70]. Energy Concepts Company estimated that when produced in-country where wages are low and transportation costs can be reduced, the ISAAC (11 m^2) can be produced for less than US$ 7000 [72].

3.7. Burkina Faso

Some vulgarisation activities of the adsorption refrigeration technology have been conducted by the Swiss NGO “Centre Écologique Albert Schweitzer” of Ouagadougou (CAES-BF). The research activities have been mainly carried by some Europeans partners of the NGO. Based on various research activities conducted since the 80s by the CNRS (France), the LESBAT (Switzerland) has built in 1999 a demonstration prototype (Fig. 20) and various labscale prototypes whose development leads to a solar SR that could be assembled in developing countries [73–75]. At least two prototypes have been successfully tested in Ouagadougou (latitude 12.3°N, Burkina Faso, Sahel country).

The first one is based on activated carbon/methanol, was built in 1999 and tested in Ouagadougou [74]. The main characteristics of the machine are presented in Table 2. A part from the vacuum technology, the complete unit can be locally built. A typical measurement of the tests, which last 3 weeks in Ouagadougou, has been reported in detail [75]. The temperature difference between condenser and ambient air is always less than 5 °C. The evaporator remains at 0 °C, or below, all the day long. The author reported solar COPs in the range 0.09–0.13, depending on the weather conditions during the three weeks (insolation: 19–25 MJ m^{-2}; average temperature: sunrise: 27.4 °C, mid-afternoon: 37.4 °C). They also reported that the use of a ventilation damper opened at night-time to increase the nocturnal cooling of the collector-adsorber, increases the performance of the refrigerator by roughly one third. This ventilation damper is intended to be the single moving part of the refrigerator. The use of vacuum insulation panels (VIPs) with a thickness of 40 mm allows an optimal volume of the cold cabinet. A comparison is made with a similar machine tested in Agadir (see Section 3.2) and the COPs are similar.

In summer 2002, another refrigerator, this time using silicagel/water (Fig. 20) as working pair was tested in Ouagadougou [76]. The valve that separates the high and low pressure vessels have been designed by the LESBAT. It is automatic and has no electronic control [75].

In the same year, the CEAS-BF implemented a market study in Burkina Faso. The result indicated that more than hundred refrigerators could be sold every year during three years to NGOs, hospitals, hotels and farmer cooperatives as long as the price is

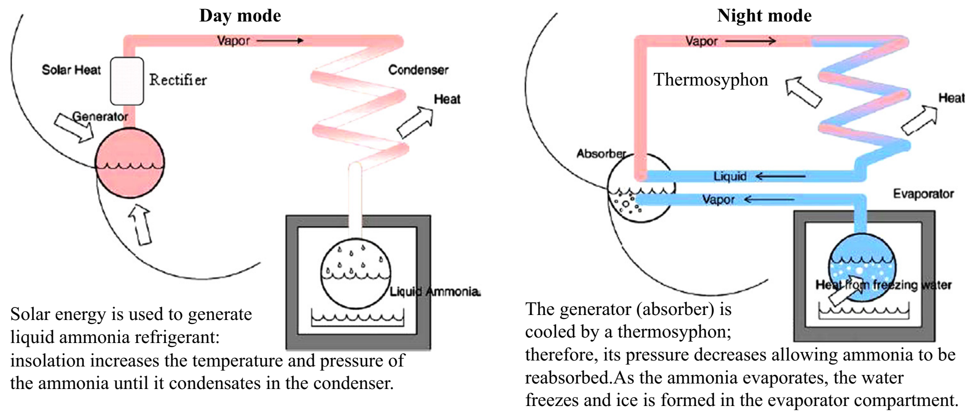


Fig. 19. Schematic and operating principle of the ISAAC solar ice maker [70].

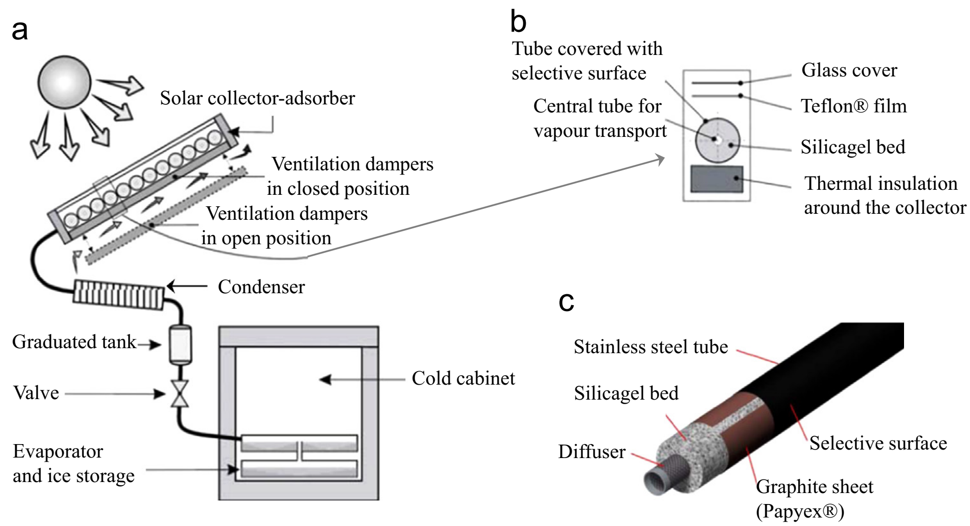


Fig. 20. Schematic of an adsorptive solar refrigerator tested in Ouagadougou [74].

less 1150€ [75]. Therefore, the challenge is to be able to produce the machine locally with a local qualified man power without exceeding the price [75].

The machine has been brought in 2009 into the market under the name "SOLAREF" (Fig. 21). The promotion is based on the cooperative trade concept, created by SOLAREF [73]: refrigerators could be sold only when the local population is trained for the assembly, the installation and the reparation of the devices. The main features of the refrigerators (two commercial models) are given in Table 3. They are designed to keep cold vaccines and foods for three consecutive days for extreme temperature conditions, such as 43 °C in day time and 34 °C at night-time [73], after five consecutive sunny days (daily average: 30 MJ m^{-2}). No maintenance is required and the refrigerator is without any mechanical moving part and no human action for the daily operation is required. Although SOLAREF received several prestigious prizes [73] for the product, in 2010, SOLAREF showed its disappointment and reported that only about ten refrigerators has been sold in African countries since they have started [77]. According to the promoter, the acquisition of the refrigerators by hospitals is usually a part of long, complex and difficult financial engineering [77]. It is sometimes easier for a sanitary centre to buy new vaccines than preserve those that have been already bought.

Some research activities on solar cooling systems for applications in Africa are currently carried at the International Institute for Water and Environmental Engineering (2iE) by the Solar Energy and Energy Savings Laboratory (LESEE). In this sense, a prototype of solar adsorption cooling system has been set up on the site of the LESEE located at Kamboinsé (Ouagadougou, Burkina Faso). This prototype consists of solar thermal collectors of 15 kW and provides a peak cooling power of 8 kW. The main target here is to demonstrate the economic feasibility of solar cooling in a West African context. The prototype is under testing for the moment and the results from these experimentations will be released in coming papers.

3.8. The ATC solar vaccine refrigerator

Though this SAdIM is not developed in Africa, it is designed for developing countries and mainly for African countries. We decide to report it because of its simplicity and available detailed documentation on the complete design of the refrigerator that could provide valuable helps for new designers of SAdIM. In collaboration with a student design team from the Michigan State University, the technology development and promotion organisation "Appropriate Technology Collaborative" (ATC, a non-profit organisation) has created a low cost solar vaccine refrigerator (Fig. 22) [78,79]. The refrigerator operates with activated carbon/ethanol to store vaccines in a temperature range of 2–8 °C, using solar thermal collectors. Activated carbon can be obtained by using coconut shells. Ethanol can be found in alcoholic beverages available locally: these beverages are made from locally available

cheap raw materials such as sugarcane, rice, palm, coconut, etc. [78,79]. When solar energy is not available, the refrigerator could operate with biofuels or wood fire. After the initial vacuum charging, the refrigerator is designed to work without human intervention or maintenance for three to five years [80]. The first prototype, which was built in five days by a student team in Guatemala, consists of a steel flat plate solar collector, tubular copper condenser with fins and tubular copper evaporator (Fig. 22) [80]. Here, 17 kg of activated carbon was directly poured in the adsorber, on contrary to the most above described machines where the adsorbent is installed in tubes. Where materials like copper tubing may be difficult to obtain, the authors suggest using aluminium or steel tubing. The latest design uses steel pipes filled with activated charcoal instead of a steel box in the original prototype. The round shape of pipe is structurally superior to a flat box so that thinner material and fewer joints are needed to be welded [81]. A comprehensive set of instructions for the construction of the refrigerator, including the full list of required pieces, is freely available online [80]. A production price of about US$ 400 is evaluated by the designers though the first hand made prototype required around US$ 1100.

Fig. 21. Photograph of a SAdIM of SOLAREF in Ouagadougou [73].

Table 3
Data on both models of commercial refrigerators SOLAREF [73,77,84].

Model	SR70	SR200
Capacity of the cold cabinet	70 l	200 l
Solar collector area	1×1 m^2	2×1 m^2
Price	5500–6600 € ex-Tax [a] [77,84]	8400 € ex-Tax [a] [84]
Volume of the refrigerator	1 m^3	–
Weight (empty)	150 kg	–

[a] Lower prices were initially suggested [73]: SR70: 2600 € ex-Tax; SR200: 3700 € ex-Tax.

4. Conclusion

The overview of solar powered sorption refrigeration technologies in Africa shows that a lot of works have been done and they were mainly concentrated on intermittent cycles, especially SAdIM. In several countries, the technological and scientific skills for the design, construction, installation and maintenance of this kind of process have been developed, though they need to be strengthened particularly in vacuum technology and hot water plumbing sectors. This is a good starting point for cost reduction studies. Indeed, although SAdIM are a technical success, they are usually bought by NGOs for health related applications (vaccines and drug storage) because they are still too much expensive for an effective market introduction and a large scale utilisation. Therefore, their cost reduction is mandatory and needs a focus. The first efforts could be concentrated on the generator as solar collector array is reported to be the most expensive part of all solar refrigeration systems [82,83]. For the cost of the materials, AC/methanol, which could be produced locally, is widely used because it is not expensive and allows reaching easily low temperature while requiring low peak regeneration temperatures (of about 100 °C). However, it operates under vacuum, a know-how that is not always easily available in African countries. The

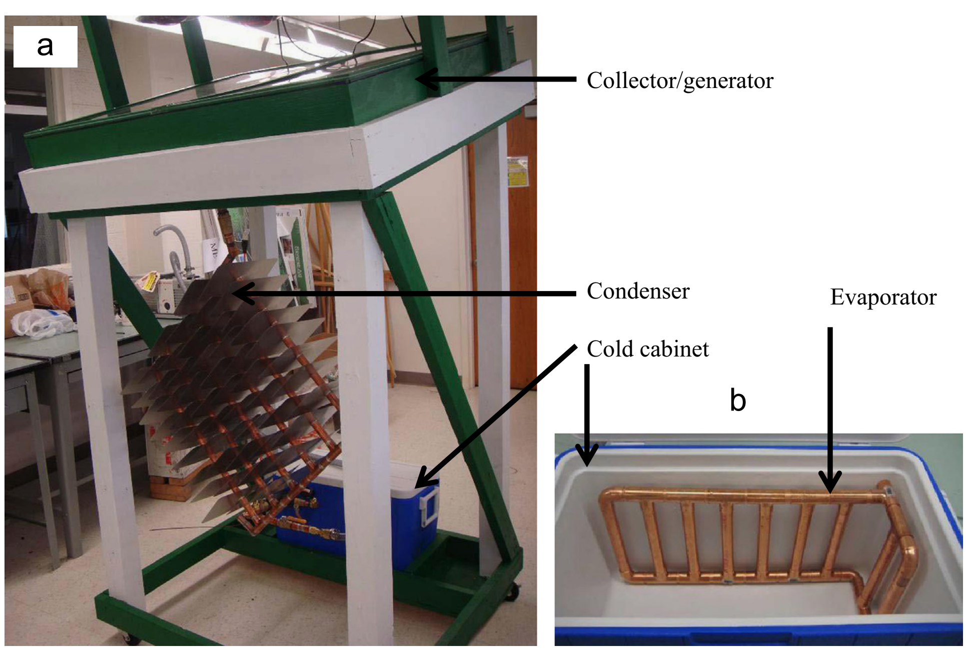


Fig. 22. (a) ATC solar vaccine refrigerator with (b) a view inside the cold cabinet [80].

working pair that operates above atmospheric pressure and retains the attention of research teams in Africa is $CaCl_2/NH_3$. A higher temperature level is however necessary for the operating of a process based on this working pair.

The performance of a solar powered sorption refrigerator strongly depends on the climate and Mediterranean climate (South Africa and Northwest Africa) seems to be regions that mostly lend themselves to SAdIM in Africa. A more adequate design for each of other climatic zones may then be relevant. Technico-economic analyses including exergetic analysis in the African context could be useful tools for this purpose.

A part from desiccant cooling applications, which have also focused research efforts especially in Egypt, no building air conditioning application has been reported. This is a potential research field where low power units represent the majority of the potential market (residential), although the service to hotels, hospitals and administrative buildings are certainly the places of introduction of this type of technology in Africa. Furthermore, continuous operating concepts, such as the one proposed by Hassan et al. [59] or integrating cold storage needed to be implemented.

On a completely different note, as for other research areas, research on solar sorption technologies in Africa suffers from a lack of coordination. The networking of researchers and structuring of the research system in Africa for synergistic collaborations would be profitable for an appreciable contribution of fundamental and applied research to African economic and social development.

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